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Feasibility study of wind energy potential in two provinces of Iran: North and South Khorasan

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ABSTRACT

In this study, the measured wind speed data for year 2007 at 10 m, 30 m and 40 m heights for two provinces of Iran, North and South Khorasan, have been statistically analyzed to determine the potential of wind power generation. This paper presents the wind energy potential at four zones in these provinces, Bojnourd, Esfarayen of North Khorasan province and Nehbandan, and Fadashk of South Khorasan province. The objective is to evaluate the most important characteristic of wind energy in the studied sites. The statistical attitudes permit us to estimate the mean wind speed, the wind speed distribution function, the mean wind power density in the sites at the height of 10 m, 30 m and 40 m. Also, three new types of wind rose diagrams were shown.

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Contents

1. Introduction

1.1. Renewable energy

There are many examples of energy: mechanical, electrical, thermal, chemical, magnetic, nuclear, biological, tidal, geothermal, and so on. Renewable energy is generated from natural resources which are renewable (naturally replenished). Atmospheric and environ-

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mental pollution as a result of extensive fossil fuel exploitation in almost all human activities has led to some undesirable phenomena that have not been experienced before in known human history. Industrialized societies have become increasingly dependent on fossil fuels for myriad uses. Modern conveniences, mechanized agriculture, and global population growth have only been made possible through the exploitation of inexpensive fossil fuels. Securing sustainable and future energy supplies will be the greatest challenge faced by all societies in this century.

Unfortunately, traditional fossil fuel energy use has had serious and growing negative environmental impacts, such as the greenhouse effect, global warming, air pollution, climate change, ozone layer depletion, acid rain, deforestation, and overall global environmental degradation [1]. Above all, the continued use and combust of fossil fuels that emit greenhouse gases (GHGs) pose a threat of particular global concern, namely human-induced climate change. The phenomenon of global climate change has resulted in a significant rise in earth surface temperatures. according to the Fourth assessment report of the intergovernmental Panel on Climate Change (IPCC), the rise was 0.74 °C during the twentieth century and is predicted to rise significantly higher this century if GHG emissions are not curbed – up to 4.0 °C under the IPCC high emissions scenario (IPCC 2007). The projected consequences of such an average temperature rise include climatic extreme events like floods, droughts, serious sea level rises, and melting of the polar ice sheets. in order to alleviate the consequences cited above, substantial reductions in GHG emissions – ranging from 60% to 80% – may be necessary, which imply a major energy transition to clean energy sources, defined as increased energy efficiency and renewable energy [2]. Additionally, fossil fuel reserves are not infinite or renewable; the supply is limited. Without a doubt, there will be significant changes in our society's modern energy infrastructure by the end of the twenty-first century. A future mix that includes sustainable energy sources will contribute to our prosperity and health. Our future energy needs must be met by a mix of sustainable technologies that have minimal environmental impacts [1].

Since 1970 it has been understood scientifically by experiments and research that these phenomena are closely related to fossil fuel uses because they emit greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) which hinder the long-wave terrestrial radiation from escaping into space and, consequently, the earth troposphere becomes warmer. In order to avoid further impacts of these phenomena, the two main alternatives are either to improve the fossil fuel quality thus reducing their harmful emissions into the atmosphere or, more significantly, to replace fossil fuel usage as much as possible with environmentally friendly, clean, and renewable energy sources [3].

Due to a growing world population and increasing modernization, global energy demand is projected to more than double during the first half of the twenty-first century and to more than triple by the end of the century. Presently, the world's population is nearly 7 billion, and projections are for a global population approaching 10 billion by midcentury. Future energy demands can only be met by introducing an increasing percentage of alternative fuels.

As mentioned above, renewable energy denotes a clean, non-toxic energy source that cannot be exhausted. The primary renewable energy sources are the Sun, wind, biomass, tides, waves, and the Earth's heat (geothermal). Solar energy is referred to as renewable and/or sustainable energy because it will be available as long as the Sun continues to shine. Estimates for the life of the main stage of the Sun are another 4–5 billion years. Wind energy is derived from the uneven heating of the Earth's surface due to more heat input at the equator with the accompanying transfer of and rain. In this sense, rivers and dams for hydro energy are stored solar energy. Another aspect of solar energy is the conversion of sunlight into biomass by photosynthesis. Animal products such as whale oil and biogas from manure are derived from this form of solar energy. Tidal energy is primarily due to the gravitational interaction of the Earth and the moon. Another renewable energy is geothermal, due to heat from the Earth generated by decay of radioactive particles from when the solar system formed. Volcanoes are fiery examples of geothermal energy reaching the surface of the Earth from the hot and molten interior.

Overall, about 14% of the world's energy comes from biomass-primarily wood and charcoal, but also crop residue and even animal dung for cooking and some heating. This contributes to deforestation and the loss of topsoil in developing countries [1].

Fossil fuels are stored solar energy from past geological ages (i.e., ancient sunlight). Even though the quantities of oil, natural gas, and coal are large, they are finite and resources are sufficient to power the industrialized world anywhere from a few more decades to a few more centuries, depending on the resource. There are also large environmental costs associated with fossil fuel exploitation – from habitat loss and destruction due to strip mining and oil spills to global warming of the atmosphere largely caused by the combustion by-product of carbon dioxide. The advantages of renewable energy are many [1]: sustainability (cannot be depleted), ubiquity (found everywhere across the world in contrast to fossil fuels and minerals), and essentially nonpolluting and carbon free. The disadvantages of renewable energy are: variability, low density, and generally higher initial cost for conversion hardware. For different forms of renewable energy, other disadvantages or perceived problems are: visual pollution, odor from biomass, perceived avian issues with wind plants, large land requirements for solar conversion, and brine from many geothermal sources.

Renewable energy sources are expected to become economically competitive as their costs already have fallen significantly compared with conventional energy sources in the medium term, especially if the massive subsidies to nuclear and fossil forms of energy are phased out. Finally, new renewable energy sources offer huge benefits to developing countries, especially in the provision of energy services to the people who currently lack them. Up to now, the renewable sources have been completely discriminated against for economic reasons. However, the trend in recent years favors the renewable sources in many cases over conventional sources.

The advantages of renewable energy are that they are sustainable (non-depletable), ubiquitous (found everywhere across the world in contrast to fossil fuels and minerals), and essentially clean and environmentally friendly. The disadvantages of renewable energy are its variability, low density, and generally higher initial cost. For different forms of renewable energy, other disadvantages or perceived problems are pollution, odor from biomass, avian with wind plants, and brine from geothermal. In contrast, fossil fuels are stored solar energy from past geological ages. Even though the quantities of oil, natural gas, and coal are large, they are finite and for the long term of hundreds of years they are not sustainable. The world energy demand depends, mainly, on fossil fuels with respective shares of petroleum, coal, and natural gas at 38%, 30%, and 20%, respectively. The remaining 12% is filled by the non conventional energy alternatives of hydropower (7%) and nuclear energy (5%). It is expected that the world oil and natural gas reserves will last for several decades, but the coal reserves will sustain the energy requirements for a few centuries. This means that the fossil fuel amount is currently limited and even though new reserves might be found in the future, they will still remain limited and the rate of energy demand increase in the world will require exploitation of other renewable alternatives at ever increasing rates. The desire to use renewable energy sources is not only due to their availability in many parts of the world, but also, more empathetically, as a result of the fossil fuel damage to environmental and atmospheric cleanness issues. The search for new alternative energy systems has

increased greatly in the last few decades for the following reasons [3]:

1. The extra demand on energy within the next five decades will continue to increase in such a manner that the use of fossil fuels will not be sufficient, and therefore, the deficit in the energy supply will be covered by additional energy production and discoveries.
2. Fossil fuels are not available in every country because they are unevenly distributed over the world, but renewable energies, and especially solar radiation, are more evenly distributed and, consequently, each country will do its best to research and develop their own national energy harvest.
3. Fossil fuel combustion leads to some undesirable effects such as atmospheric pollution because of the CO_2 emissions and environmental problems including air pollution, acid rain, greenhouse effect, climate changes, oil spills, etc. It is understood by now that even with refined precautions and technology, these undesirable effects can never be avoided completely but can be minimized.

The renewable sources have also some disadvantages, such as being available intermittently as in the case of solar and wind sources or fixed to certain locations including hydropower, geothermal, and biomass alternatives. Another shortcoming, for the time being, is their transportation directly as a fuel. These shortcomings point to the need for intermediary energy systems to form the link between their production site and the consumer location, as already mentioned above [3].

1.2. Wind energy in Iran

It is known that the supplies of fossil fuels are limited and their utilization as energy sources causes environmental degradation due to incomplete combustion when used as energy source, in addition to this as the world population increases the demand for energy sources increases, therefore the issue of a gradual replacement of fossil fuels with renewable energy sources is of major consideration for most countries: studies and evaluations regarding the wind potential estimation in Iran illustrates that in 26 sections of the country (including more than 45 suitable sites) the nominal capacity of the sites, considering a general efficiency of 33% is approximately 6500 MW, however, it is noteworthy that the nominal capacity of all power plants of the country is already 3400 [4]. Utilization of renewable energy sources in Iran began a decade ago and it is still in its initial stages of development.

Condition of Iran's geographical is such that its low air pressures produce strong air flows over it in general during the summer and winter months in comparison with high pressures in the north and northwestern areas. It is the difference in the air pressure between the atmosphere over Iran, central Asia as well as the Atlantic Ocean during the winter months that causes cold winds from north and humid air flows from the Atlantic and Mediterranean from west. Since these systems of air maldes collide with the humid air from the Mediterranean, it produces snow over the country. Iran is also influenced by winds from the Atlantic Ocean on the northwest and by the winds from the Indian Ocean from the southeast during the summer; of the well known winds from the east are the 120 day winds of Sistan and lavas wind: other local winds in the country include the north winds on the Persian gulf and Khoch bad winds in the Gorgan plain, deez wind between Mashhad and Nayshabour and Sham winds in Khuzestan [5].

The potential energy of wind is estimated to be about 6500 MW in Iran. As a matter of fact this level of energy is considered to be of medium level among different countries. At the present time most developed countries, which have wind energy potential similar to those in Iran are taking advantage of this power at an accelerating rate. Presently more than 23 billion kWh of cheap, clean and development sources electricity are being produced annually across the world. Germany, for example, produced some 4400 MW of electricity with wind, while Iran with a similar level of available wind power produces only 10 MW. The related figure for India, neighboring country, is 1000 MW [6].

Iran's first experience in installing and using modern wind turbines dates back to 1994. Two sets of 500 kW Nordtank wind turbines were installed in Manjil and Roodbar. They produced more than 1.8 million kWh per year. These two sites are in the north of Iran, 250 km from Tehran, the capital of Iran. The average wind speed is 15 m/s for 3700 h per year in Roodbar, and 13 m/s for 3400 h per year in Manjil. After this successful experience, in 1996 the contract for 27 wind turbines was signed and they were installed by 1999 in Manjil, Roodbar and Harzevil. Harzevil is the third wind farm site near to Manjil. Manjil is about 800 m above sea level and Harzevil is about 500 m higher there are 21 installed wind turbines in Manjil, 1× 500 kW, 5× 550 kW and 15× 300 kW [7].

When mean wind speed is in the range of 5–25, technical usage of wind power would be possible. Producible potential of wind power in the world is estimated about 110 Ej (each Ej equals to 1018 J), 40 MW of which is the capacity installed by the end of 2003 (1382-solar calendar) all over the world.

In 2006, Iran generated 47 MW of electricity from wind power (ranked 30th in the world). This was a 47% increase over 32 MW in 2005. Total wind generation in 2004 was 25 MW out of 33,000 MW total electrical generation capacity for the country. In 2008, Iran's wind power plants in Manjil (in Gilan province) and Binaloud (in Khorasan Razavi province) produce 82 MW of electricity per year. By 2009, Iran had wind power installed capacity of 91 MW [8].

Assessment of wind energy potential in Iran has been done for some areas such as Manjil in Gilan province [9], Yazd [10], Tehran [11], and Semnan [12] provinces; there are also studies about feasibility of offshore wind turbine installation in Iran and comparison with the world [13], future of renewable energies in Iran [14] and renewable energy issues in Middle East compared with Iran [15]; and the present study shows feasibility of wind energy potential in another suitable provinces.

1.3. North and South Khorasan

Fig. 1. Map of Iran (North and South Khorasan have been highlighted).

North and South Khorasan are two of the three provinces that were created after the division of Khorasan in 2004 (Fig. 1). North

Fig. 2. Map of North Khorasan [17].

Khorasan ("Khorasan-e Shomali") is one of the 30 provinces of Iran, located in the northeastern part of the country. The city of Bojnourd is the center of the province. Other counties are Shirvan, Esfarayen, Maneh-o-Samalqan (Ashkhaneh), Jajarm, Faruj and Germeh (Fig. 2).

North Khorasan province contains many historical and natural attractions, such as mineral water springs, small lakes, recreational areas, caves and protected regions, and various hiking areas. Most of the historical relics are from the Qajar era, as earthquakes continue to ravage older relics. Some of the popular attractions of North Khorasan are, Sari Gol protected area, Ghaisar and Solak old castles, Noshirvan and Ebadatgah caves, Faghatdezh castle, Tomb of Sheikh Ali Esfarayeni, Saloog Protected Area, Besh Ghardash (five brothers) and Baba-Aman springs, Bidag, Konegarm, Konjekooh, Armadloo and Seyed Sadegh caves, Mofakham mirror house, Baba Tavakol mausoleum, Imamzadeh Sultan Seyed Abbas, Salook Protected Area and Bazkhaneh Valley [16].

The province of North Khorasan is bordered from east and south by the province of razavi Khorasan, from north, country of Turkmenistan, from southwest, Semnan province, and west, Golestan province.

South Khorasan ("Khorasan-e Jonoubi") is a province located in eastern Iran. Birjand is the center of the province. The other major cities are Ferdows and Qaen (Gaeen).

South Khorasan province consists of 8 counties: Birjand, Boshruyeh, Ferdows, Qaen, Sarayan, Nehbandan, Darmian and Sarbisheh (Fig. 3). South Khorasan is also other one of the three provinces that were created after the division of Khorasan in 2004.

The province of South Khorasan is bordered from east to country of Afghanistan, from north, Razavi Khorasan province, from west, Yazd province, southwest, Kerman and from southeast, Sistan-Baluchistan province.

We have studied the feasibility of using the wind in the different areas of North and South Khorasan provinces. The studies indicated that these two provinces have large wind potential. The locations of meteorological sites for all studied zones are in Table 1.

Fig. 3. Map of South Khorasan [17].

2. Analysis of wind data

Data collected over a period of one year, from 1/1/2007 to 12/31/2007 in the time interval of 10 min for sites corresponded to Bojnourd and Esfarayen of North Khorasan, as well as Nehbandan and Fadashk of South Khorasan. The meteorological masts with 40 m height were installed in suitable coordinates by power ministry. The data logger used has 3 sensors of velocity at 10 m, 30 m and 40 m heights and also 2 sensors of direction at 30 m and 37.5 m [4].

2.1. Mean wind speed

In the first phase of study, as shown in Table 2, annual mean wind speed in the time interval of 10 min for four different sites, Bojnourd, Esfarayen, Nehbandan, and Fadashk zones are examined.

It is observed that at higher height from the earth, mean wind velocity is higher. According these values, Esfarayen and Fadashk have the highest mean wind speed in three heights. Figs. 4–7 show the monthly mean wind speed at 10 m, 30 m and 40 m heights of sites.

The maximum and minimum of monthly mean wind speeds are desirable for three heights in Figs. 4–7.

The annual mean wind speed per one hour is demonstrated in Figs. 8–11. These figures show hours of day that have a suitable wind speed in all over the year 2007. Best wind speeds could be observed for sites in the year.

Table 1
Geological location of meteorological sites for North and South Khorasan.

Site	Latitude	Longitude
Bojnourd	37°28′	57°19′
Esfarayen	37°03′	57°29′
Nehbandan	31°32′	60°02′
Fadashk	32°78′	58°79′

Table 2
Annual mean wind speed at 3 heights for sites in North and South Khorasan (m/s).

Site	10 m	30 m	40 m
Bojnourd	4.96	5.36	5.56
Esfarayen	5.26	6.19	6.32
Nehbandan	5.05	5.68	5.86
Fadashk	5.27	6.20	6.33

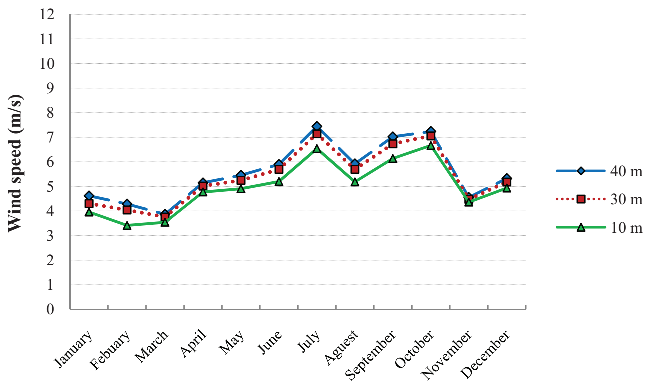

Fig. 4. Monthly mean wind speed for 3 heights of Bojnourd.

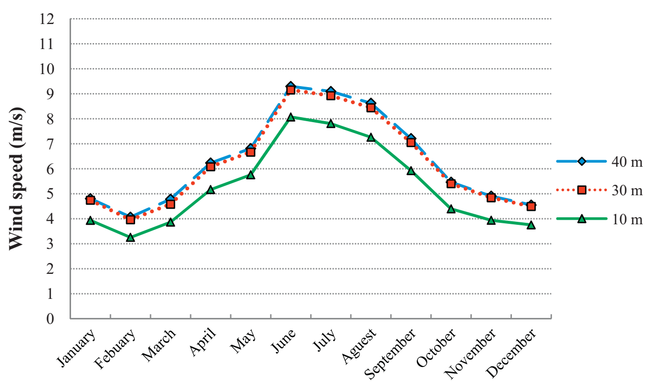

Fig. 5. Monthly mean wind speed for 3 heights of Esfarayen.

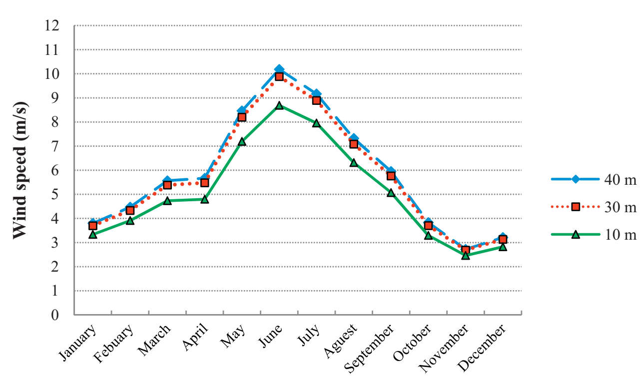

Fig. 6. Monthly mean wind speed for 3 heights of Nehbandan.

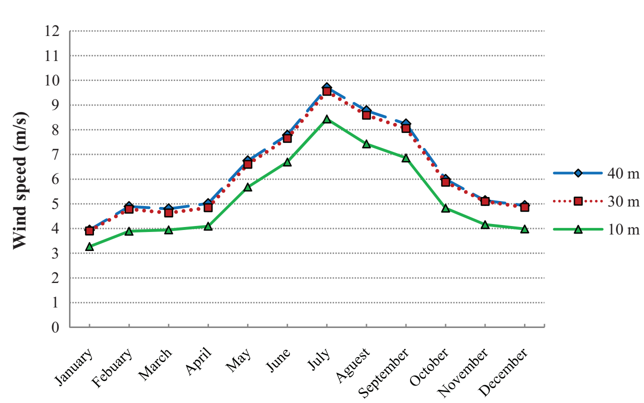

Fig. 7. Monthly mean wind speed for 3 heights of Fadashk.

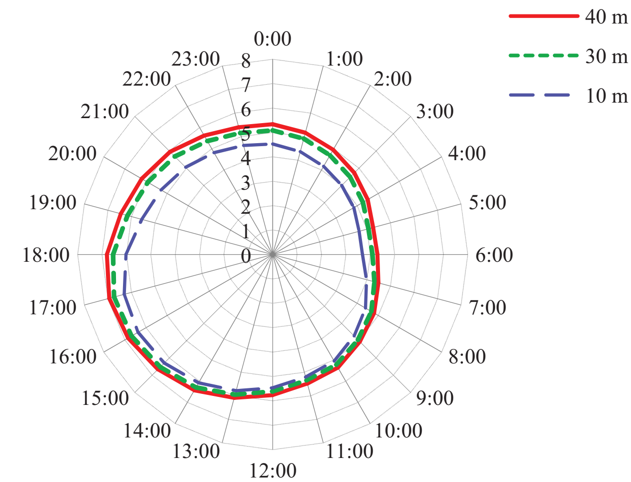

Fig. 8. Mean wind speed at different hours of the year, Bojnourd.

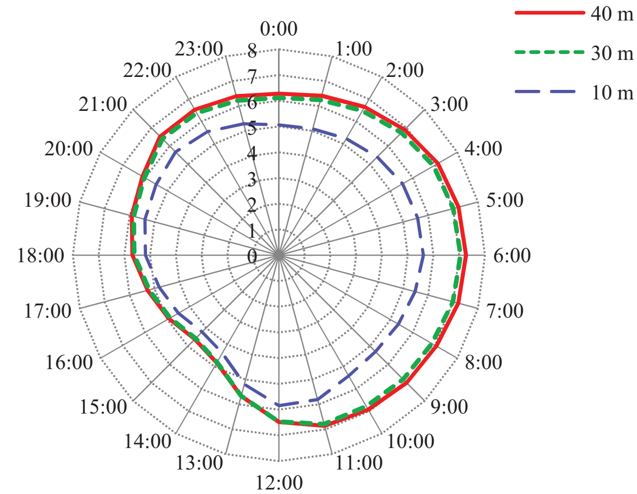

Fig. 9. Mean wind speed at different hours of the year, Esfarayen.

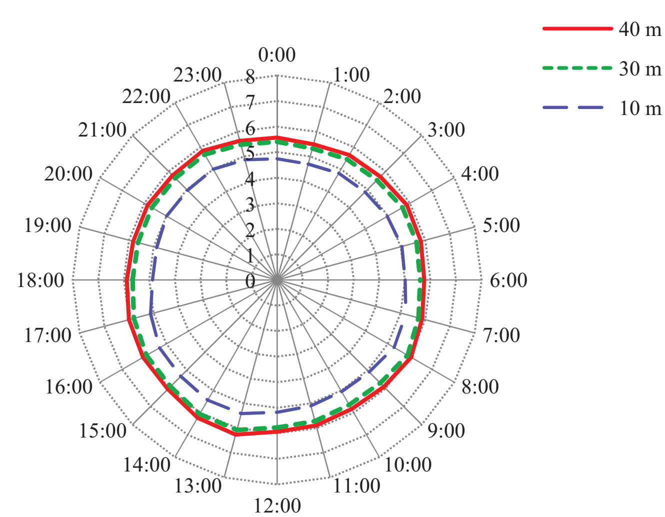

Fig. 10. Mean wind speed at different hours of the year, Nehbandan.

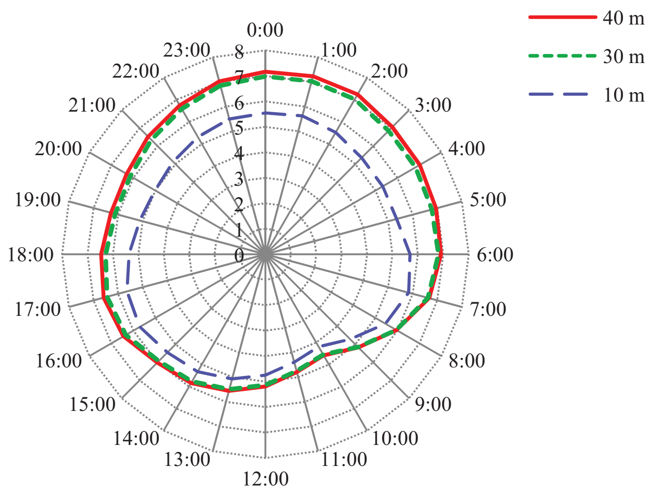

Fig. 11. Mean wind speed at different hours of the year, Fadashk.

To analyze the figures, for example Fig. 7, it is observed that the monthly mean wind speed of Fadashk site at heights 10, 30, and 40 m varies between 3.26 and 8.46 m/s, 3.9 and 9.55 m/s, and 3.94 and 9.70 m/s, respectively, that maximum and minimum of wind speed happen in July and January, respectively. According to Fig. 11, for the Fadashk site, the hourly maximum velocity for a year is related to o'clock 2 (AM) that the average of it in year 2007 and for height 40 m is equal to 7.25 m/s. Also the hourly minimum velocity for a year is related to o'clock 10 (AM) that the average of it in year 2007 and for height 40 m is equal to 4.59 m/s. For other sites can be discussed as above.

Also, it must be noted that Nehbandan has uniform hourly wind speeds in comparison with other sites.

2.2. Wind direction

The wind direction is of paramount importance for the possibility assessment of using wind energy and plays a significance role in the optimal positioning of a wind farm in a given area.

Above we have estimated the mean wind speed without evoking the influence of the direction in the distribution of this parameter. In next section, the frequency with which the wind direction falls within each direction sector is evaluated, so we present the data collected in the form of wind rose.

Changes in wind direction are due to the general circulation of atmosphere, again on an annual basis (seasonal) to the mesoscale (4–5 days).

Figs. 12–15 illustrate the monthly prevailing wind direction for height 30 m. Limitation of wind direction has a significant preference for wind powerhouse. For example, the annual mean wind directions for Fadashk are 274.35° and 275.64° at 30 m and 37.5 m,

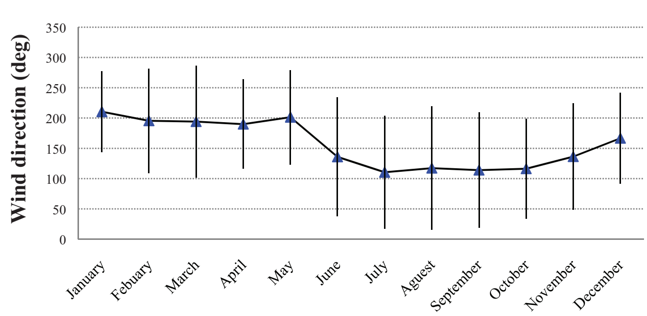

Fig. 12. Monthly mean wind direction and standard deviation at 30 m, Bojnourd.

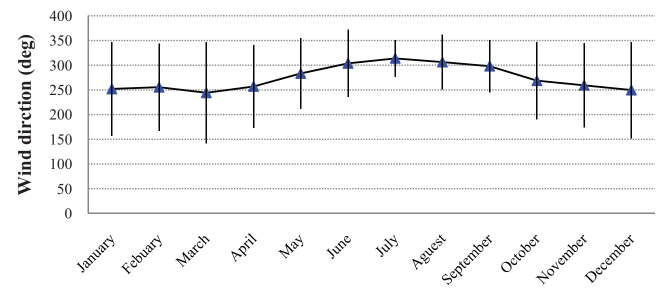

Fig. 13. Monthly mean wind direction and standard deviation at 30 m, Esfarayen.

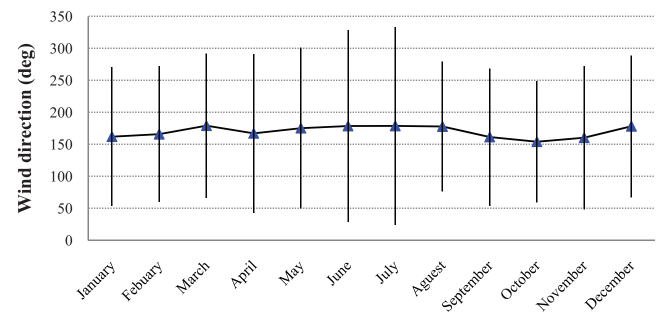

Fig. 14. Monthly mean wind direction and standard deviation at 30 m, Nehbandan.

respectively. Based on, the annual mean wind directions are almost the same at these two heights.

In these figures were shown the standard deviation for monthly wind direction. It must be noted that since the standard deviation is less, site has better conditions.

2.3. Wind rose

A common wind rose is a diagram showing the temporal distribution of wind direction and azimuthal distribution of wind speed at a given location. A wind rose is a convenient tool for displaying anemometer data (wind speed and direction) for sitting analysis. Fig. 16 illustrates new forms of wind rose, which consists of several equally spaced concentric circles with 12 equally spaced radial lines (each represents a compass point). The line length (circle radius) can show wind speed, mean wind speed, or frequency of wind speed. In polar diagrams, are used from wind speed or mean wind speed, whereas in rose diagram is used the frequency of wind speed. The rose diagram displays the frequency of wind in direction. In Fig. 16 the speeds are in dimension (m/s). The comparison of the polar diagrams with rose diagram shows, in direction that wind has highest frequency; the wind has highest speed.

For example, as shown in Fig. 16b, almost 18,000 of wind speed data in height 30 m are in directions between 300° and 330°.

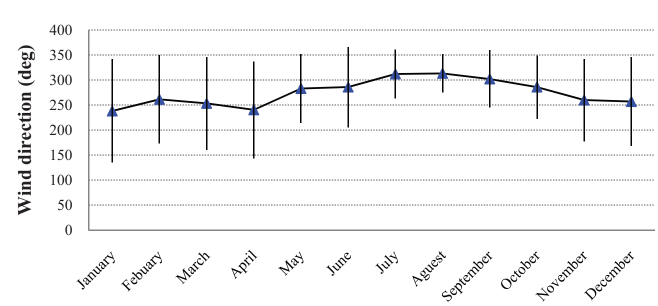

Fig. 15. Monthly mean wind direction and standard deviation at 30 m, Fadashk.

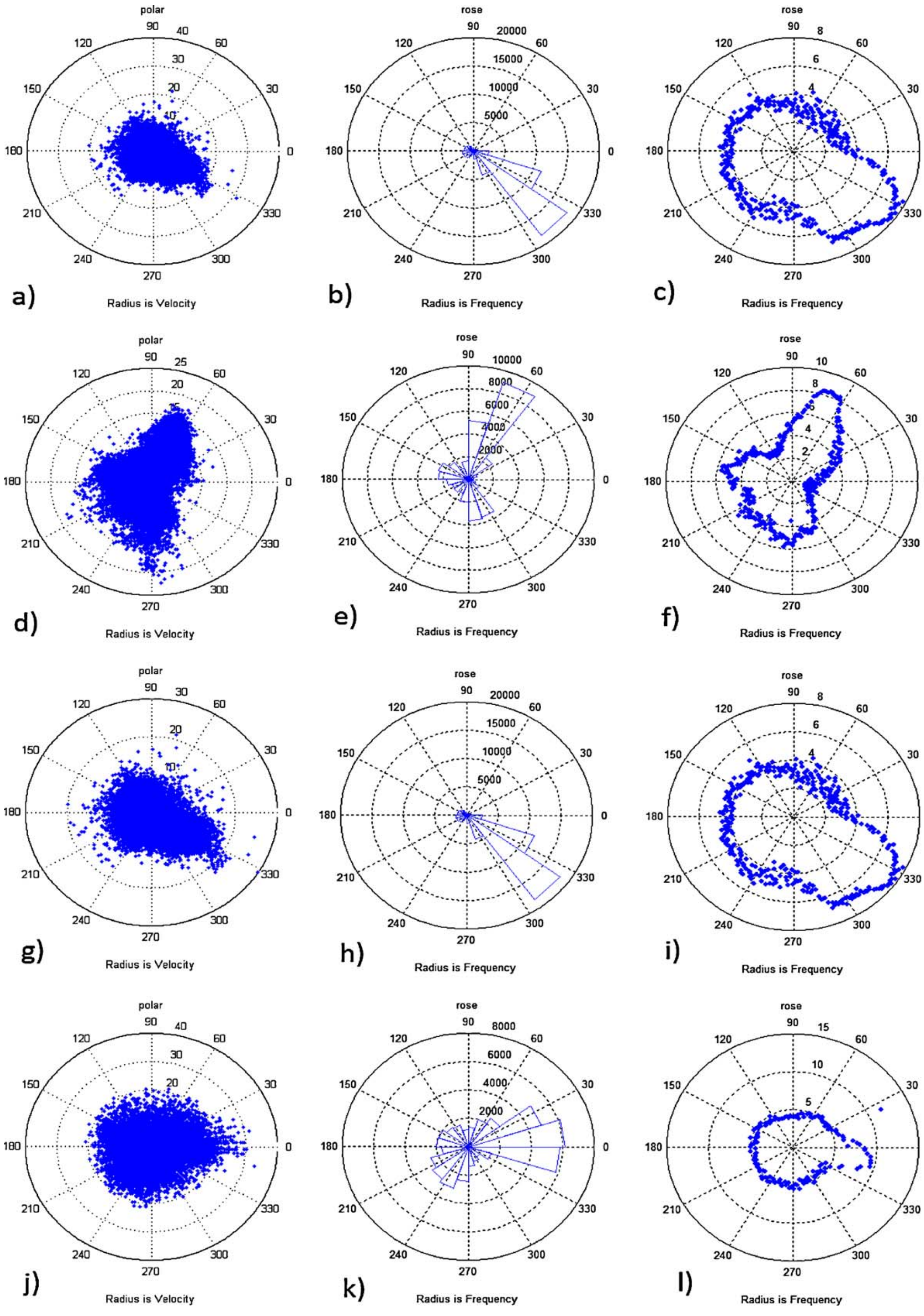

Fig. 16. Wind rose of Fadashk, Bojnourd, Esfarayen, and Nehbandan, Fadashk (a–c), Bojnourd (d–f), Esfarayen (g–i), and Nehbandan (j–l).

2.4. Turbulence

Turbulence in the wind is caused by dissipation of the wind's kinetic energy into thermal energy via the creation and destruction of progressively smaller eddies (or gusts). Turbulent wind may have a relatively constant mean over time periods of an hour or more, but over shorter times (minutes or less) it may be quite variable. Turbulence can be thought of as random wind speed fluctuations imposed on the mean wind speed. These fluctuations occur in all three directions: longitudinal (in the direction of the wind), lateral

Table 3
Annual weibull parameters (k, c) and other results for the sites of North and South Khorasan.

Site	Parameter	10 m	30 m	40 m
Bojnourd	k	1.69	1.73	1.75
	c	5.57	6.02	6.25
	Wind speed at max. frequency (m/s)	3.3	3.7	3.9
	Percent of max. frequency	14%	13.1%	12.67%
	Max of turbulence	4.3	2.55	2.3
	Mean of turbulence	0.1685	0.1476	0.1369
Esfarayen	k	1.93	2.02	2.01
	c	5.94	7.00	7.14
	Wind speed at max. frequency (m/s)	4	4.9	5
	Percent of max. frequency	14.11%	12.33%	12.06%
	Max of turbulence	5.5	3.1	2.8
	Mean of turbulence	0.2046	0.1624	0.1598
Nehbandan	k	1.34	1.33	1.32
	c	5.51	6.19	6.37
	Wind speed at max. frequency (m/s)	1.9	2.2	2.3
	Percent of max. frequency	13.33%	11.86%	11.52%
	Max of turbulence	12	12	11.5
	Mean of turbulence	0.2586	0.233	0.225
Fadashk	k	1.93	2.02	2.02
	c	5.95	7.01	7.15
	Wind speed at max. frequency (m/s)	4.1	5	5.1
	Percent of max. frequency	14.13%	12.33%	12.07%
	Max of turbulence	5.5	3.2	3.1
	Mean of turbulence	0.2041	0.1661	0.1634

(perpendicular to the average wind), and vertical. Existence of turbulence decreases the power, causes the fatigue stress in the wind turbine too. Besides the mean wind speed, the variability of a set of data is represented by the standard deviation.

2.4.1. Turbulence intensity

The most basic measure of turbulence is the turbulence intensity. It is defined by the ratio of the standard deviation of the wind speed to the mean [19].

$$\mathrm{TI} = \frac{\sigma_U}{\bar{U}} \tag{1}$$

The length of this time period is normally no more than an hour, and by convention in wind energy engineering it is usually equal to 10 min. The study of a wind speed time history measured with sufficiently high resolution enables its most important parameters to be defined. Turbulence intensity changes with the mean wind speed, with the surface roughness, with the atmospheric stability and with the topographic features [20].

Ignoring short term fluctuations, the level of prevailing wind speed determines the mean wind speed $\bar{U}$. It is generally averaged over a period of 10 min. Thus, the turbulence is the instantaneous, random deviation from the mean wind speed. The maximum and average of turbulence intensity are seen in Table 3. Also in Fig. 17 are shown the turbulence intensity in each measurement period.

2.5. Wind speed distribution

Statistical analysis can be used to determine the wind energy potential of given sites and estimate the wind energy output at these sites. To describe the statistical distribution of wind speed, various probability functions can be suitable for wind regimes. According to Gumbel [18], weibull distribution is the best one, with an acceptable accuracy level. This function has the advantage of making it possible to quickly determine the average of annual production of a given wind turbine. The weibull probability density function is given by [19]:

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^{k}\right] \tag{2}$$

The determination of the weibull probability density function requires knowledge of two parameters: k, shape factor and c, scale factor. Analytical and empirical methods are used to find k and c, such as Justus formulas demonstrated in the following form [19]:

$$\sigma_U = \sqrt{\frac{\sum_{i=1}^{N}(U_i - \bar{U})^2}{N-1}} \tag{3}$$

$$k = \left(\frac{\sigma_U}{\bar{U}}\right)^{-1.086}, \qquad \frac{c}{\bar{U}} = \frac{k^{2.6674}}{0.184 + 0.816k^{2.73855}} \tag{4}$$

where σ_U and $\bar{U}$ represent the standard deviation and mean wind speed, respectively. Standard deviation also is defined through the value of k [19]:

$$\sigma_U = \bar{U}\sqrt{\left(\frac{\Gamma(1+2/k)}{\Gamma^2(1+1/k)} - 1\right)} \tag{5}$$

Table 3 shows one year weibull parameters (k: dimensionless, c: m/s) and other results for the four areas of North and South Khorasan provinces.

It must be noted that the weibull distribution gives a good fit to experimental data. Weibull distributions for Fadashk reveal that the wind speed 4.1, 5 and 5.1 m/s have the highest wind frequency at 10 m, 30 m and 40 m during the year with frequency being equal to 14.13%, 12.33% and 12.07%, respectively.

As more can be said in weibull distribution, expansion of curve leads to higher speeds and illustrates that produced energy of this site is desirable.

One way to define the probability density function is that the probability of a wind speed occurring between U_a and U_b is given by [19]:

$$p(U_a \le U \le U_b) = \int_{U_a}^{U_b} p(U)\,dU \tag{6}$$

Also, the total area under the probability distribution curve is given by:

$$\int_0^{\infty} p(U)\,dU = 1 \tag{7}$$

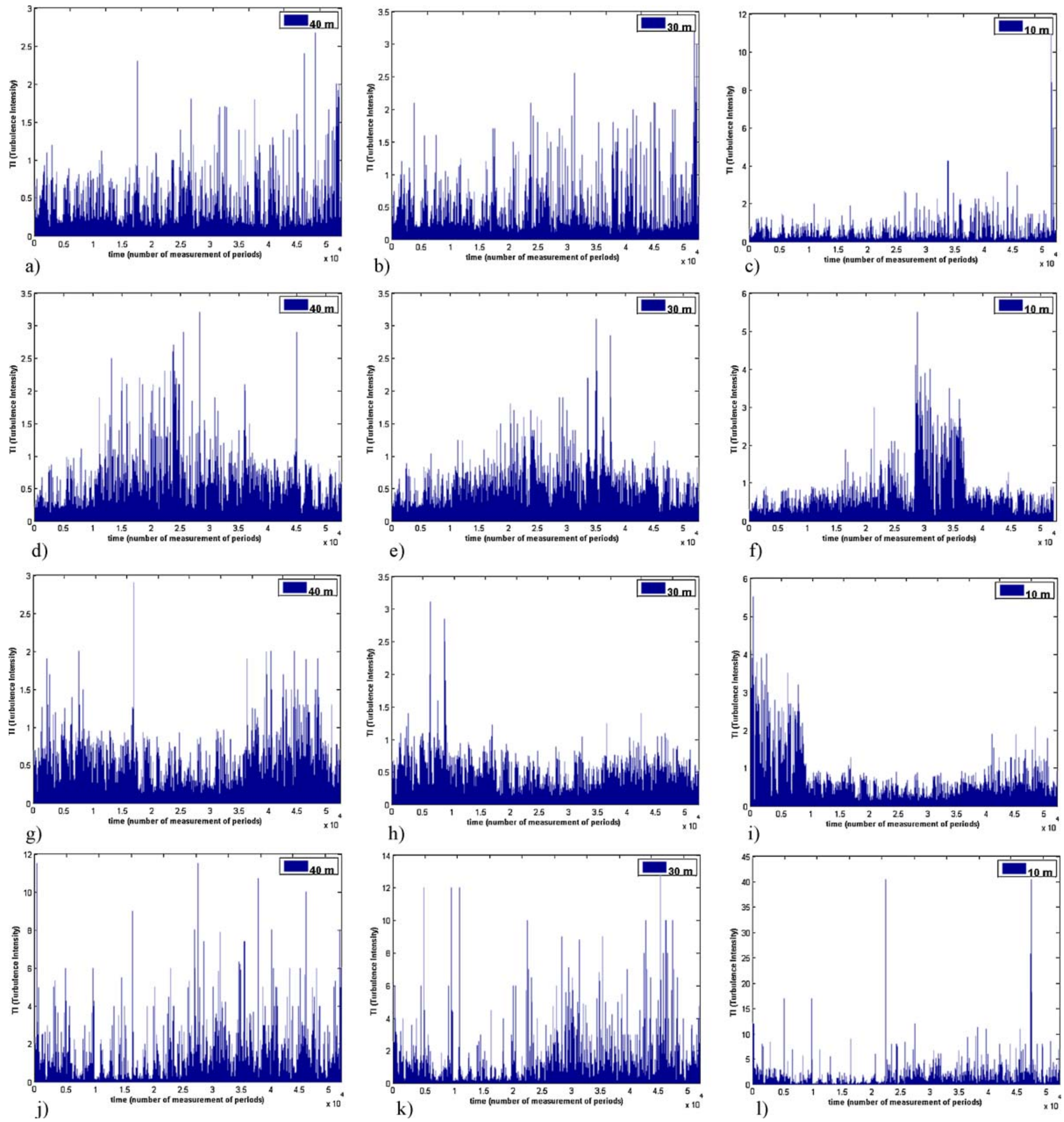

Fig. 17. Turbulence intensity of Bojnourd, Fadashk, Esfarayen, and Nehbandan, Bojnourd (a–c), Fadashk (d–f), Esfarayen (g–i), and Nehbandan (j–l).

Table 4
Probability density function ($P(2.5\,\text{m/s} < U < 25\,\text{m/s})$).

Sites	10 m	30 m	40 m
Bojnourd	77.29	80.41	81.74
Esfarayen	82.79	88.2	88.58
Nehbandan	70.67	73.95	74.62
Fadashk	82.93	88.29	88.67

For example, the probability of a wind speed happen upper than 2.5 m/s is shown in Table 4. Because many of wind turbines drive between the cut in and cut out speed equal to 2.5 m/s and 25 m/s, respectively.

2.6. Surface roughness

Although there are a number of ways to arrive at a prediction of a logarithmic wind profile (e.g., mixing length theory, eddy viscosity theory, and similarity theory), a mixing length type analysis given by Wortman (1982) is by the log law [19]:

$$\frac{U(z)}{U(z_r)} = \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \tag{8}$$

where $U(z)$ is the wind speed at height z, $U(z_r)$ is the reference wind speed at reference height z_r, and z_0 is the surface roughness length, which characterizes the roughness of the terrain. The power law represents a simple model for the vertical wind speed profile. It is basic form is:

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{9}$$

According to Eq. (9), the quantity of α can be obtained by curve fitting.

Also with respect to mean wind speeds at 10 m, 30 m and 40 m, and curve fitting with Logarithmic profile (log law), it can be found the equivalent surface roughness length of terrain. It was shown for these areas in Table 5.

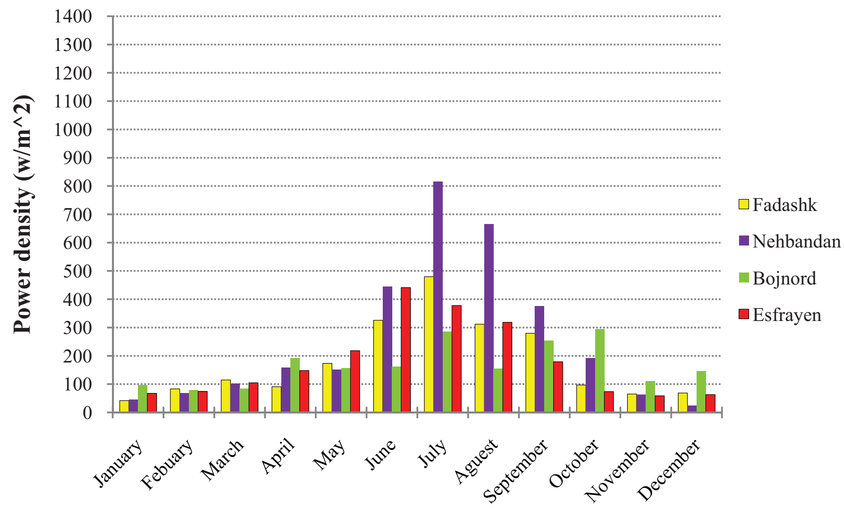

Fig. 18. Monthly power density at 10 m.

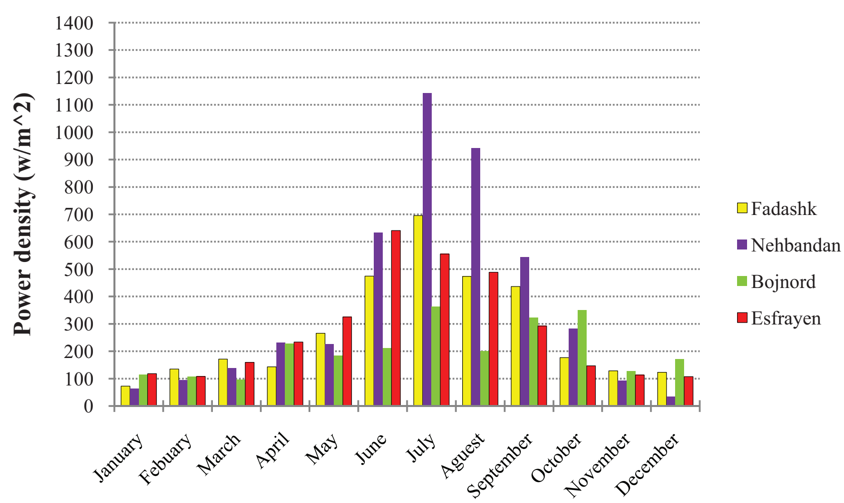

Fig. 19. Monthly power density at 30 m.

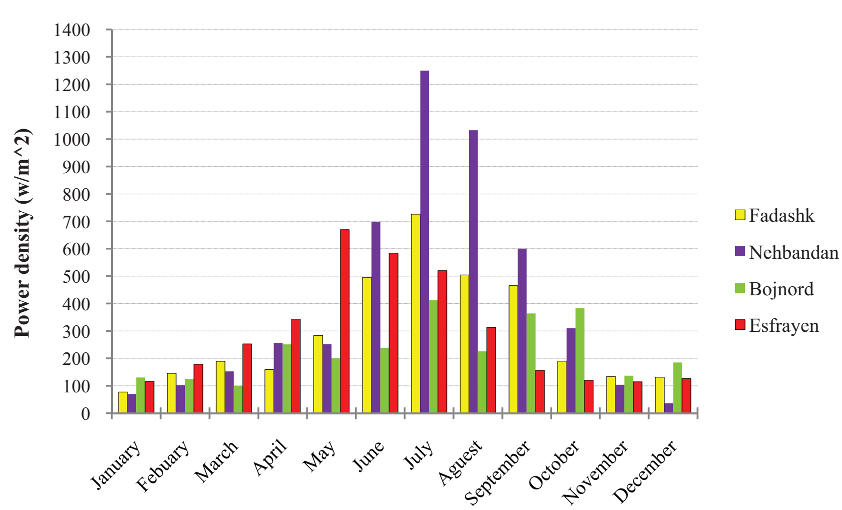

Fig. 20. Monthly power density at 40 m.

Table 5
Surface roughness and α.

	Bojnourd	Esfarayen	Nehbandan	Fadashk
Surface roughness (mm)	0.044	80.68	4.75	83.34
α	0.07721	0.1837	0.1208	0.1848

2.7. Power and energy density

The best way to evaluate the wind resource available at a potential site is by calculating the wind power density. It indicates how much energy is available at the site for conversion to electricity by a wind turbine. The wind power per unit area, P/A or wind power density is [19]:

$$\frac{\bar{P}}{A} = \frac{1}{2}\rho \int_{c}^{\infty} U^3 p(U)\,dU = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \approx \frac{1}{2}\rho\overline{U^3} \tag{10}$$

And also wind energy density is:

$$\frac{\bar{E}}{A} = \left(\frac{\bar{P}}{A}\right)(N\,\Delta t) \tag{11}$$

where N is the number of measurement periods, Δt.

For standard conditions (sea level, ISOC) the density of air is 1.225 kg/m^3. Figs. 18–20 show the monthly wind power density at the 3 heights. There are mainly two ways to estimate the power density in the site. The first is based on the measured data and the second on the probability distribution function. However, the first method is more precise because of its uses.

2.8. Monthly power density

In Figs. 18–20 the monthly power density at 3 heights are determined by measured data for four areas that mentioned above; and it is found that maximum monthly power density for each figure is related to mid months of year 2007.

2.9. Annual power and energy density

The yearly power density is determined using Eq. (10), and also energy density per unit area can be calculated from:

$$E_w = \sum_{i=1}^{N} P_w(U_i)(\Delta t) \tag{12}$$

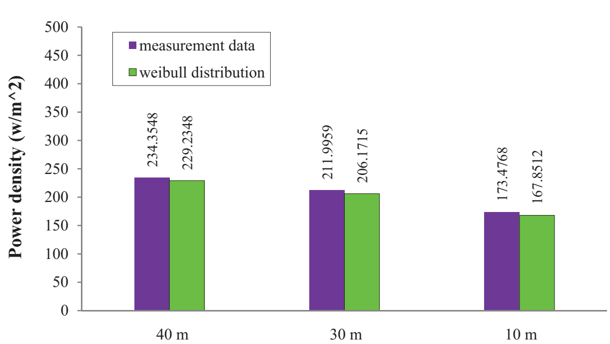

Fig. 21. Annual power density at 10 m, 30 m and 40 m – Bojnourd.

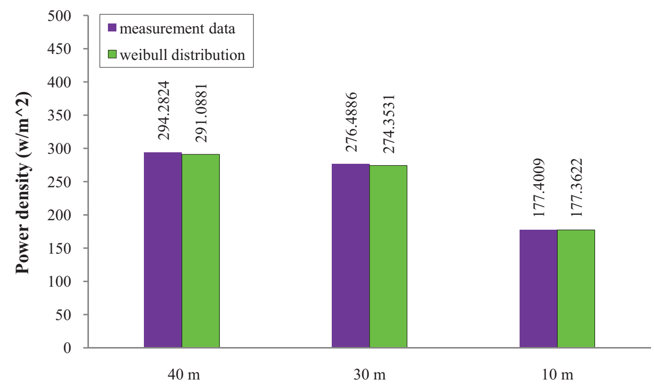

Fig. 22. Annual power density at 10 m, 30 m and 40 m – Esfarayen.

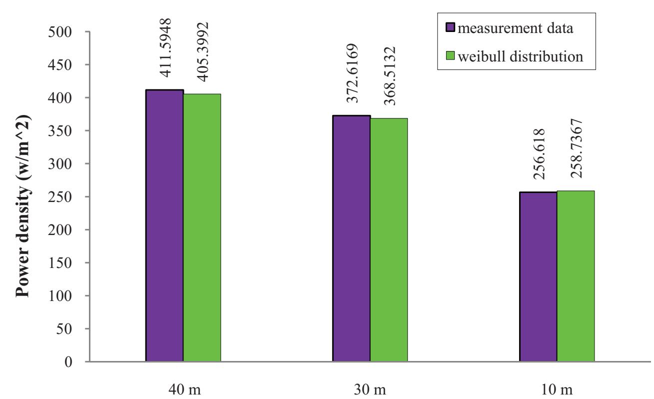

Fig. 23. Annual power density at 10 m, 30 m and 40 m – Nehbandan.

Some sample qualitative magnitude evaluations of the wind resource are [19]:

$$\frac{\bar{P}}{A} < 100\,\mathrm{W/m^2} - \text{poor}$$
$$\frac{\bar{P}}{A} \approx 400\,\mathrm{W/m^2} - \text{good}$$
$$\frac{\bar{P}}{A} > 700\,\mathrm{W/m^2} - \text{great}$$

From above criteria, it is found that the sites have a relatively good situation with respect to power density. Figs. 21–24 also compare the results from the measurement data and weibull distribution and found little difference between them. Difference between annual energy density and annual power density is only in a time coefficient, thus this was not considered.

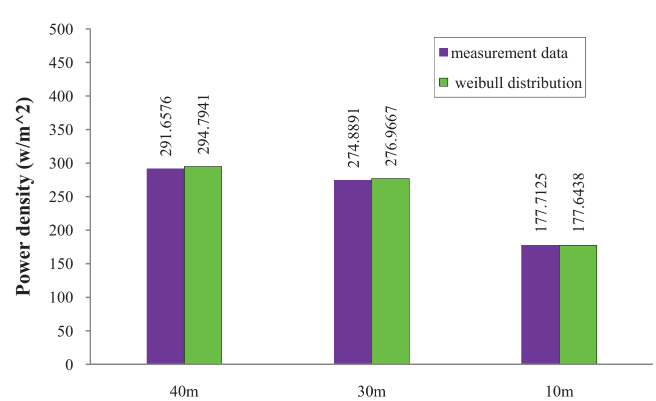

Fig. 24. Annual power density at 10 m, 30 m and 40 m – Fadashk.

3. Conclusion

Detailed statistical study of wind at 10 m, 30 m and 40 m heights in North and South Khorasan provinces is presented. The most important outcomes of the study can be summarized as follows:

1. Wind speeds are modeled using weibull probability function; the weibull parameters k (dimensionless) and c (m/s) are shown in Table 3.
2. The results and parameters of weibull distribution show that these provinces have good conditions.
3. Three new types of wind rose diagrams were shown. The wind Rose analysis showed the prevailing wind directions for 30 m height.
4. An evaluation of the wind resource available in Bojnourd that is class 2 and Esfarayen, Nehbandan, and Fadashk are class 3 wind power sites, (with consideration to wind power density classes published by U.S. Department of Energy) indicates its suitability for both grid connection and stand alone activities such as water pumping and battery charging.

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